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Methods

MAASSD: Methodology for Agent-based modelling for Agricultural System Simulation in Developing Countries

Mahamadou Belem[1]

1 *Mahamadou BELEM, Université Nazi BONI, Laboratoire d'Analyse, de Mathématiques Discrètes et d'Informatique, Bobo-Dioulasso, Burkina Faso*
Corresponding author: Mahamadou Belem (mahamadou.belem@gmail.com)

Abstract

Modelling agricultural systems in developing countries is attracting particular attention, as the models provide policy-makers with a relevant framework for ex ante analysis of their decision-making processes, enabling them to develop policies to address future challenges such as climate change and population growth. Agent-based modelling (ABM) is increasingly being used for this purpose. ABM enables the simulation of the heterogeneity of farmers' decision-making processes and the interactions between human decision-making processes and the environment. However, despite the wide use of ABM in simulating agricultural systems in developing countries, a clear methodology is still lacking. Current applications of ABM in agricultural system simulations are disparate and cannot be replicated in other contexts. This study aims to propose a unique methodology for agent-based modelling of agricultural systems in developing countries. The resulting methodology, 'MAASSD' (Methodology for Agent-based Modelling for Agricultural System Simulation in Developing Countries), is generic and multi-scale, taking into account multi-stakeholder engagement for knowledge integration and sharing. Our methodology is based on existing methodologies and provides a unique approach to agricultural system modelling using ABM. However, MAASSD methodology differs from these existing methodologies with regard to agricultural systems. The methodology has been tested in the simulation of the feedback loop between agricultural dynamics and migration in Burkina Faso, demonstrating its robustness. In future, the MAASSD methodology will be tested in a large number of contexts to demonstrate its effectiveness in representing agricultural systems in developing countries.

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Key words: Agent-based model, agricultural system, meta-model, modelling framework, simulation

Introduction

Modelling agricultural systems in developing countries is attracting particular attention, as these models provide policy-makers with a useful framework for analysing their decision-making processes in advance. This enables them to develop policies to address future challenges, such as climate change and population growth.

The agricultural system is complex, characterised by a set of interacting actors at different spatial and temporal scales. For example, farmers interact with each other to share information and resources such as labour, seeds and inputs. They also interact through markets for various purposes and with policy-makers.

Sometimes, these interactions take the form of organisations, such as farmers' organisations and non-governmental organisations. These interactions contribute to knowledge acquisition, which could improve farmers' decision-making. Farmers in the agricultural system differ in terms of their characteristics (e.g. farm size and labour force) and their decision-making processes (e.g. cropping systems, crop rotation and food and money management). They interact with the environment, modifying its state. For example, farmers modify soil structure and fertility through their cropping systems. Loss of soil fertility leads to decreased soil productivity, which constrains farmers to change their cropping system.

Today, ABM is widely used in agricultural system simulation (Bousquet and Le Page 2004; Sajjad et al. 2016; Belem and Saqalli 2017; Mora-Herrera et al. 2021). ABM enables the simulation of the heterogeneity of farmers' decision-making processes and the interactions between human decision-making processes and the environment. In addition, "ABMs are adapted to the context of "developing" countries: The low availability of quantitative data and the difficulty of launching statistically reliable investigations limit the use of statistical or multi-criteria optimization models" (Belem et al. 2015).

In fact, an ABM is characterised by a set of interacting agents. The agents are heterogeneous as they differ by their characteristics and decision-making. In addition, the agents interact with their environment (Weyns et al. 2005, 2006). Agents can modify the state of their environment that, in return, constrain the agents to change their decision-making. Finally, the agents evolve into organisations that constrain their interactions and decision-making (Ferber et al. 2004; Belem and Müller 2013).

Although there is a large use of ABM in agricultural system simulation, we still miss a clear methodology for agent-based modelling of agricultural system in developing countries. Most studies are based on specific methodology difficult to replicate in other contexts. Langrell et al. (2013) according to Kremmydas et al. (2018) "found that, although there is a substantial increase of ABMs models over time, a large number of existing farm level models are developed for specific purposes and locations and are not easily adaptable and reusable (for policy evaluation)".

The objective of this paper is to propose a specific agent-based modelling methodology for agricultural system simulation. Through this paper, we aim to enhance ABM for agricultural system simulation; standardise agricultural system modelling using ABM; and propose a general framework for knowledge modelling, sharing and integration from the perspective of multiple stakeholders.

The paper is organised as follows. The next section presents the specification of the methodology. After, the paper presents how the study has been achieved. The proposed methodology is presented and finally, a case study is discussed.

Specification of the study

The proposed methodology should be generic**,** representing a large number of agricultural systems in developing countries.

It should take into account the knowledge integration and sharing. The multiplicity of actors – farmers, decision-makers, researchers - pursuing various objectives and interlinked dynamics require the integration of various types of knowledge – from different actors – for a better understanding of the problem to be solved. The methodology to be developed should be able to provide guidance

and tools for knowledge sharing and integration from different stakeholders. In order to achieve this specification, we propose using ontology and an integrated modelling approach. Additionally, we advocate the use of participatory approach.

It should be multi-scale. A multi-scale analysis is important to deal with interactions between human and environmental systems. Reynolds et al. (Reynolds et al. 2007) argued that the involvement of multiple stakeholders, with highly differing objectives and perspectives, illustrates the need to pay attention to the multilevel, nested and networked nature of Human-Environment systems. The present document proposes a methodology for identifying the relevant scales in agricultural system modelling.

It should allow for the multi-formal representation of agricultural systems, as the dynamics of these systems depend on the interactions between social, economic, environmental and policy dynamics. The main question that arises is how to integrate socio-economic and environmental dynamics with policy interventions. Representing these various dimensions requires an integrated model of a different nature, which is where the multi-formalism approach comes in. Multi-formalism simulation enables heterogeneous models of the same system, as perceived at different scales, to be integrated (Duboz et al. 2003; Duboz 2004). This increases model reuse and turns models into collaborative tools for scientists from different disciplines.

It should integrate the heterogeneity of farmers: farmers in the agricultural system are heterogeneous. They differ in terms of their cropping system decisions and characteristics. They also do not respond in the same way to policy decisions. Taking account of this heterogeneity enables us to assess the different impacts that farmers have on the agricultural system and to develop policies for different groups of farmers. In this study, we assume that farmers are heterogeneous and propose a conceptual model to represent this.

Materials and methods

Methodology

Firstly, a literature review has been done in order to answer to the following questions (Table 1) about what are the main methodologies in MAS and ABM?

1. How the different studies on MAS and ABM for agricultural system simulation take the different components of agricultural system?

The research has been done in scholar.google and sciencedirect in order to extract the main papers. The most relevant papers published between 2000 and 2025 have been selected for the study.

Table 1. Criteria of papers selection.

Questions of research	Key words used and their combination
What are the main methodologies in MAS and ABM?	(Multi-agents systems or MAS or Agent-based modelling or ABM) and (methodology)
How the different studies on MAS and ABM for agricultural system simulation take the different components of agricultural system?	(Multi-agents systems or MAS or Agent-based modelling or ABM) and (agricultural system) and (component)

For the first criteria, 13 papers have been selected taking account their relevance. These papers have been divided in two groups. The first group concerns methodologies for MAS engineering (Table 2) and the second group concerns methodologies for social sciences simulation (Table 3).

Considering the second criterion, we took into account papers that modelled the features that define the agricultural system (Table 3). Antle et al. (2017) identified the following five components: cropping systems, livestock production, socio-economic dimensions and environmental and policy dimensions. Twenty-four relevant papers were selected for this purpose.

Proposed methodology

Robinson et Dilkina (2004) identified three representational forms of models. The first form of model is the mental model (MM). They are used by humans on a daily basis in fundamental types of learning and decision-making. The second form of model is the communicative model (CM). It is used as a support for communication and data sharing between different persons involved in the modelling process. They are consensual and explicit, allowing different persons to have the same understanding of the representation of the system. The communicative models are commonly used in software engineering (SE) and in knowledge engineering (KE). SE mainly uses

Table 2. MAS and ABM methodologies.

	Short name	Year	Title	Source
1	(Abrami et al. 2006)	2006	ORIGAMI, une méthode organisation centrée de modélisation multi-agent de systèmes complexes.	Rev. Int. Géomat.
2	(Bernon et al. n.d.)		The ADELFE Methodology For an Intranet System Design.	
3	(Bresciani et al. 2004)	2004	Tropos: An Agent-Oriented Software Development Methodology.	Auton. Agents Multi-Agent Syst.
4	(Cossentino et al. 2007)	2007	A Holonic Metamodel for Agent-Oriented Analysis and Design, Manufacturing,	Lecture Notes in Computer Science.
5	(Da Silva and De Lucena 2003)	2003	MAS-ML: a multi-agent system modelling language.	in: Companion of the 18th Annual ACM SIGPLAN Conference on Object-Oriented Programming, Systems, Languages, and Applications.
6	(DeLoach 2004)	2004	Methodologies and Software Engineering for Agent Systems, Multiagent Systems, Artificial Societies and Simulated Organizations.	Kluwer Academic Publishers, Boston
7	(Etienne 2009)	2009	Co-construction d'un modèle d'accompagnement selon la méthode ARDI: guide méthodologique.	Laudun Cardère Éditeur.
8	(Evans et al. 2001)	2001	MESSAGE: Methodology for engineering systems of software agents.	EURESCOM EDIN 0223–0907.
9			The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication and structural realism.	J. Artif. Soc. Soc. Simul.
10	(Huget et al. 2004)	2004	The AUML Approach.	Methodologies and Software Engineering for Agent Systems,
11	(Pavón et al. 2005)	2005	The INGENIAS methodology and tools.	in: Agent-Oriented Methodologies. IGI Global
12	(Trencansky and Cervenka 2005)	2005	Agent Modelling Language (AML): A comprehensive approach to modeling MAS.	Informatica 29.

Table 3. Case studies of ABM application in Agricultural System Simulation.

	Short name	Year	Title	Source
1	(Amadou et al. 2018)	2018	Simulating agricultural land-use adaptation decisions to climate change: An empirical agent-based modelling in northern Ghana.	Agric. Syst.
	(Bommel 2009)	2009	Définition d'un cadre méthodologique pour la conception de modèles multi-agents adaptée à la gestion des ressources renouvelables	(PhD Thesis). Université Montpellier II-Sciences et Techniques du Languedoc.
2	(Badmos et al. 2015)	2015	An Approach for Simulating Soil Loss from an Agro-Ecosystem Using Multi-Agent Simulation: A Case Study for Semi-Arid Ghana.	Land
3	(Barbuto et al. 2019)	2019	Improving diffusion in agriculture: an agent-based model to find the predictors for efficient early adopters.	Agriculture food
4	(Bazzana et al. 2022)	2022	Impact of climate smart agriculture on food security: An agent-based analysis.	Food Policy
5	(Belem et al. 2018)	2018	Simulating the Impacts of Climate Variability and Change on Crop Varietal Diversity in Mali (West-Africa) Using Agent-Based Modelling Approach.	Journal of Artificial Societies and Social Simulation
6	(Belem et al. 2011)	2011	CaTMAS: A multi-agent model for simulating the dynamics of carbon resources of West African villages.	Ecol. Model.
7	(Belem and Saqalli 2017)	2017	Development of an integrated generic model for multi-scale assessment of the impacts of agro-ecosystems on major ecosystem services in West Africa.	J. Environ. Manage.
8	(Berger 2001)	2001	Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis.	Agric. Econ.
9	(Catarino et al. 2021)	2021	Fostering local crop-livestock integration via legume exchanges using an innovative integrated assessment and modelling approach based on the MAELIA platform.	Agric. Syst.
10	(Coronese et al. 2023)	2023	AgriLOVE: Agriculture, land-use and technical change in an evolutionary, agent-based model.	Ecol. Econ.
11	(Ding and Achten 2022)	2022	Coupling agent-based modelling with territorial LCA to support agricultural land-use planning.	J. Clean. Prod.
12	(Grillot et al. 2018)	2018	Agent-based modelling as a time machine to assess nutrient cycling reorganisation during past agrarian transitions in West Africa.	Agric. Syst.
13	(Hirata Sanches et al. 2022)	2022	An integrated model to study varietal diversity in traditional agroecosystems.	Plos One
14	(Kremmydas et al. 2018)	2018	A review of Agent Based Modelling for agricultural policy evaluation.	Agric. Syst.
15	(Lloyd and Chalabi 2021)	2021	Climate change, hunger and rural health through the lens of farming styles: an agent-based model to assess the potential role of peasant farming.	Lancet Planet. Health
16	(Parker et al. 2003)	2003	Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: A Review.	Ann. Assoc. Am. Geogr.
17	(Quang et al. 2014)	2014	Ex-ante assessment of soil conservation methods in the uplands of Vietnam: An agent-based modelling approach.	Agric. Syst.
18	(Rebaudo et al. 2010)	2010	Agent-Based Modelling of Human-Induced Spread of Invasive Species in Agricultural Landscapes: Insights from the Potato Moth in Ecuador.	**Journal of Artificial Societies and Social Simulation**
19	(Saqalli et al. 2011)	2011	Targeting rural development interventions: Empirical agent-based modelling in Nigerien villages.	Agric. Syst.
20	(Schreinemachers et al. 2007)	2007	Simulating soil fertility and poverty dynamics in Uganda: A bio-economic multi-agent systems approach.	Ecol. Econ.
21	(Steel et al. 2014)	2014	To weed or not to weed? The application of an agent-based model to determine the costs and benefits of different management strategies.	Plant Prot. Q.
22	(Troost 2015)	2015	Agent-based modelling of climate change adaptation in agriculture: a case study in the Central Swabian Jura.	
23	(Zhang and DeAngelis 2020)		An overview of agent-based models in plant biology and ecology.	Ann. Bot.
24	(Zhang et al. 2025)	2025	Farmers' decisions on crop residues utilisation, greenhouse gases reduction and subsidy of crop residue-based bioenergy: An agent-based life cycle model.	Sustain. Prod. Consum.

conceptual models in UML to describe the object structures (using class diagram) and the dynamics (using state charts, activity diagrams etc.). A conceptual model provides orientation on how the software should meet a need and specification of the behaviour of the system under construction (Dieste et al. 2001). KE mainly uses logics, frame-like languages and, more recently, the ontologies. An ontology is an explicit specification of the conceptualisation of a domain (Gruber 1995). "An ontology defines the basic terms and relations comprising the vocabulary of a topic area as well as the rules for combining terms and relations to define extensions to the vocabulary" (Neches et al. 1991). The third form of model is the simulation model (SM). An SM is an experimental tool allowing to conduct "experiments with this model for the purpose either of understanding the behaviour of the system or of evaluating various strategies (within the limits imposed by a criterion or a set of criteria) for the operation of the system" (Shannon 1998). Concretely, a simulation model is a software programme simulating the behaviour of a system that it is supposed to represent. It can be viewed "as a representational continuum from the most concrete to the most abstract" (Robinson and Dilkina 2018). This classification clearly draws the process from the idea of the system to model (the mental model) up to its concrete realisation (the simulation model) through successive concretisations of the representations (the more or less detailed communicative models).

In this study, we are concerned by the development of the conceptual model and simulation model. Then, the methodology to be proposed in this study should allow us to develop both a conceptual model and simulation model.

Our general approach is based on agent-based modelling. Our main aim is to propose a unique methodology for agricultural system modelling using agent-based modelling. This methodology takes into account the social, economic, environmental and politic dimensions of agricultural system. In addition, the methodology takes into account the multi-scale representation and agricultural system and the stakeholders involvement.

To support the development of the conceptual model and the simulation model, we use the Unified Modelling Language (UML). "The objective of UML is to provide system architects, software engineers and software developers with tools for analysis, design and implementation of software-based systems as well as for modelling business and similar processes" (OMG 2017). In this study, we use UML for domain analysis, the model design and implementation by making emphasis on stakeholders' engagement. Specifically, our objective is to use UML as a tool for knowledge sharing and integration between various stakeholders in agricultural system simulation as proposed by Bommel and Müller (2007).

Background

Proposing methodology that allows the design of the conceptual model and multi-agents systems or ABM is not new. These methodologies can be categorised into two (2) sub-groups: the software orientated methodology and social simulations methodologies.

Software orientated methodologies

Many methodologies have been proposed in order to deal fully with the MAS development. Amongst them, we have Ingenias (Pavón et al. 2005), Tropos (Bresciani et al. 2004), ADELFE (Bernon et al. n.d.), Message(Evans et al. 2001), Aspects (Cossentino et al. 2007) etc. Each methodology intends to resolve a specific problem of MAS development. For example, ADELFE provides a methodology and a meta-model for the self-adaptative and self-organising systems specification; Mase (DeLoach 2004) is a complete methodology allowing the development of heterogeneous systems; Aspect concerns MAS and Holonic MAS development. The language used by most methodologies is based on the extension of the UML meta-models, such as AUML (Huget et al. 2004), AML (Trencansky and Cervenka 2005), MAS-ML (Da Silva and De Lucena 2003) etc.

These methodologies are not specific to agricultural system modelling and simulation and are difficult for non-computer scientists to use. Most of the time, ABMs for agricultural system simulation are developed by non-computer scientists. Therefore, the methodology used for agricultural system simulation should align closely with the modellers' perspectives and their conception of the agricultural system.

Social simulations methodologies

The second group of methodologies, concern ARDI (Etienne 2009), ORIGAMI (Abrami et al. 2006), ODD (Grimm et al. 2020) and Bommel (Bommel 2009).

ARDI (Etienne 2009) provides a framework for describing the interactions between actors and resources. ARDI is a relevant framework for conceptual model development in the context of knowledge sharing and integration. However, the framework does not take account the simulation phase. Based on the Organisation Centred Multi-Agents System, Abrami et al. (Abrami et al. 2006) proposed the ORIGAMI methodology for modelling the renewables resources management. ORIGAMI is based on AGR meta-model, proposes a set of UML diagrams for describing the different components of a model and finally guidelines for model development and simulation. However, the ORIGAMI meta-model is too general and abstract to be easily used in agricultural system simulation.

Bommel (Bommel 2009) proposed a methodology for ABM of renewable resources management. This methodology can be used in agricultural systems. However, the methodology is specific and does not propose a meta-model to make easier the agricultural system modelling.

As to ODD or ODD+, it provides a standard methodology for ABM modelling and simulation. The objectives of ODD are to make model descriptions more understandable and complete, thereby making ABMs less subject to criticism for being not reproducible (Grimm et al. 2010). Contrary to the ARDI and ORIGAMI, ODD or ODD+ is more and more used in agricultural system simulation (Polhill et al. 2008; Kremmydas et al. 2018; Mora-Herrera et al. 2021). Asssessing papers on Agent Based Modeling for agricultural policy evaluation, Kremmydas et al. (2018) found that the majority of the papers follow the ODD protocol. However, as withother methodologies, ODD is too general to be easily applicable in agricultural system simulation. Using ODD in agricultural system simulation requires an important adaptation.

Although social simulation methodologies are not specific to the agricultural system, they provide a solid foundation for our study. For instance, ARDI enables us to identify the key stakeholders, while ODD provides a foundation for model design. However, the MAASSD methodology is specific to agricultural systems. It considers domain analysis for knowledge extraction and sharing amongst different stakeholders. Finally, unlike existing methodologies, MAASSD proposes a simulation framework and two meta-models specific to agricultural systems.

MAASSD Methodology

The methodology is composed by the following steps:

1. Step 1: system requirements aim to understand the objective of the study and to identify the main processes to be taken into account in the modelling process.
2. Step 2: domain analysis aims to understand the main information shared in the system. The main objective is to provide a common understanding of the target system. At this step, we have proposed a meta-model for representing the agricultural system.
3. Step 3: selection of tools: defines how to select appropriate tools according to the system requirements.
4. Step 4: design: the main objective of this step is to propose a methodology to design an ABM for agricultural system simulation.
5. Step 5: implementation: the main objective of this step is to propose a methodology to develop an ABM for agricultural system simulation.

Step 1: Requirements

The objective of this step is to establish the purpose of the modelling. Specifically, the main objective is to determine the system requirements. A requirement is a property that must be exhibited in order to solve real-world problems. There are two categories of requirements: a) functional requirements and b) non-functional requirements, which constrain the solution. Non-functional requirements are sometimes known as constraints or quality requirements. In our study, a functional requirement refers to the agricultural system processes to be simulated. Non-functional requirements refer to sustainability, adaptation, knowledge integration and sharing and the feedback loop between agriculture and the environment. Scales of analysis are also considered to be non-functional requirements.

Specifically, the system requirement concerns the stakeholders, processes and scales identification.

Stakeholders identification

In this study, we assume that model development is demand-driven. Since the model development is demand-driven, the modeller must identify the main stakeholders involved in the project. These stakeholders include scientists, decision-makers, modellers and local actors. The main actors on whom the system dynamics are based are identified and described, based on the perspective of the stakeholders. The ARDI method can be used to identify these actors and their interactions.

Identification of main processes of the system

The processes are organised according to the main features of the agricultural system. Antle et al. (2017) identified five components that characterise the agricultural system: cropping systems; livestock production; socio-economic factors; environmental factors; and policy factors. Table 4 summarises the list of possible processes to be considered according to these different dimensions and modelling purpose.

Once the main processes of the study have been identified, a UML use case diagram should be built. A use case diagram defines the expected behaviour of a system from the user's perspective. It can be used as a communication tool, as well as to define the scope of the study.

Scales of analysis

The objective of this step is to identify and describe the various scales of analysis. Several scales can be considered according to the modelling purpose and the processes to be simulated. Here, we propose a set of possible scales for agricultural system modelling, depending on which processes are to be taken into account.

To model crop production and nutrient cycling (carbon, nitrogen, phosphorus etc.), as well as land-use and land-cover change, two scales can be considered: the field scale and the farm scale. The field scale allows the biophysical processes, particularly the interactions between soil, plants and the atmosphere and the impact of farmers' decision-making on the soil and vice versa, to be taken into account. However, farmers' decision-making is defined at the farm level; therefore, considering the farm level allows us to take into account crop diversity management and the interactions between farmers' activities (for example, the interactions between crop and animal production).

In order to represent the role of livestock production, it is useful to consider two scales:'individual animal' and 'herd'. These scales are important from biological and economic perspectives (Breman and Ridder 1991). From a biological perspective, the aim is to understand the relationships between individual animals and the herd. The individual animal plays a key role in preserving the animal population. Animal population growth depends on individual animal fecundity. However, individual animal characteristics are driven by nutritional status, which, in turn, depends on the size of the animal population. Average production per animal increases with an improved supply of fodder. Conversely, production decreases with deteriorating nutritional status. From an economic point of view, the herd is the most common management unit in extensive farming systems, provided that it is sufficiently productive to provide the owner and their family with an adequate income (Breman and Ridder 1991).

To take into account the overall interactions between farmers and their impact, the community scale can be considered. At this level, transactions involving land, manure and labour occur, as well as the establishment of collective rules regarding land use. Several groups (e.g. ethnic and social) co-exist. Farmers' practices and access to and use of resources are influenced by their group membership. Additionally, the village is an open system that exchanges people, goods and money with the outside world. These various interactions influence community organisation, for example, the emergence of new structures, such as farmers' organisations or agricultural practices.

Table 4. Possible processes to be considered.

Processes	Studies cases
Cropping system	
Crop yield	(Berger 2001; Belem et al. 2011; Amadou et al. 2018)
Crop varietal diversity management	(Belem et al. 2018; Hirata Sanches et al. 2022)
Pest, disease and weed management	(Rebaudo et al. 2010; Steel et al. 2014)
Crop-livestock integration	(Catarino et al. 2021)
Plant growth	(Zhang and De Angelis 2020)
Irrigation management	(Cai and Xiong 2017; Nouri et al. 2019; Alam et al. 2022; Lang and Ertsen 2023)
Crop residue management	(Zhang et al. 2025)
Fertility management	(Schreinemachers et al. 2007; Quang et al. 2014)
Livestock production	
Livestock production	
Pasture and range land management	(Fust and Schlecht 2018)
Livestock disease	
Socioeconomic dimension	
Population dynamics (ageing, natality, mortality and migration)	(Belem et al. 2011; Belem and Saqalli 2017)
Income distribution and poverty	(Belem et al. 2011; Belem and Saqalli 2017)
Food and nutrition security	(Belem et al. 2011; Lloyd and Chalabi 2021; Bazzana et al. 2022)
Heath	(Gotteland et al. 2014)
Market	(Balmann 1997; Berger 2001; Coronese et al. 2023)
Land access	
Innovation diffusion	(Berger 2001; Barbuto et al. 2019; Coronese et al. 2023)
Environmental dimension	
Land-use and land-cover change	(Parker et al. 2003; Amadou et al. 2018; Ding and Achten 2022; Coronese et al. 2023)
Nutrient cycling (carbon, nitrogen, phosphorus etc.)	(Belem et al. 2011; Belem and Saqalli 2017; Grillot et al. 2018)
Climate impacts and adaptation to climate change	(Badmos et al. 2015; Troost 2015; Amadou et al. 2018; Lloyd and Chalabi 2021)
Water cycle	
Soil degradation	(Schreinemachers et al. 2007; Quang et al. 2014; Badmos et al. 2015)
Policy dimension	
Impacts of policy interventions	(Berger 2001; Saqalli et al. 2011; Kremmydas et al. 2018)
Credit access	

Step 2: Domain analysis

The objective of this step is to identify the main concepts of the target system and the problem to be solved, in order to establish a clear and shared understanding. In terms of the requirements analysis, the domain analysis focuses more on the 'what' than the 'how' of the system.

This step uses the documentation from existing studies of the target system and existing agricultural system models as inputs to extract relevant concepts. According to the study objective, the main concepts are described by outlining their characteristics and definitions. This can be achieved using a participatory approach to ensure a shared understanding of the problem amongst the different study participants.

In addition, ontologies can also be used at this stage for information extraction. A range of agricultural system ontologies have been developed to date.

For example, in the domain of agricultural domain, Agrovoc (Rajbhandari and Keizer 2012) and Crop-Pest (Rodríguez-García and García-Sánchez 2020) are used for information research and extraction in agricultural domain. Seamless (Athanasiadis et al. 2009) and PLANTS (Consortium 2002) ontologies are used for data sharing amongst the different sub-information systems. AgrODSS (Alharbi et al. 2024), IrrigaOnto (Cornejo et al. 2005), Crop-Pest (Rodríguez-García and García-Sánchez 2020) and AgriNepalData (Pokharel et al. 2014) are developed for information sharing on production techniques and for the improvement of decision making. Beck et al. (2010) used ontology for agricultural system modelling. Based on an ontology-based database and wiki semantic, Belem et al. (2015) proposed an integrated framework for knowledge acquisition, sharing and integration on land use and land management in West Africa.

Once the main concepts of the agricultural domain have been identified, a domain model is developed. This model provides a visual representation of the previously identified and described concepts and their relationships. To achieve this, we propose using a UML class diagram. At this stage, the classes only include attributes, not methods.

We then propose a meta-model that can be extended to develop a specific domain model. The proposed meta-model represents household structuration (Fig. 1), cropping system management strategies (Fig. 2), household occupations (Fig. 3) and, finally, policy intervention (Fig. 4).

Step 3: Selection of tools

The objective of this step is to identify the main tools to be used for the model development. These tools concern the models to be integrated in the target model and the modelling platform. Reviewing papers on agricultural system modelling, Mora-Herrera et al. (2021) found that most modelling and simulation platforms used in agricultural system modelling are Cormas (Bousquet et al.,1998), NetLogo (Tisue and Wilensky 2004), GAMA (Grignard et al. 2013) and Repast (Collier 2003). These platforms can be used for the model development. Although these platforms provide useful and flexible frameworks to develop models, they take only into account the implementation and simulation phases limiting their use with MAASSD.

MAASSD methodology should take account model integration. Then, for each identified process, the modeller can identify the existing models to be integrated in the model. For example, Belem et al. (2011) and Belem and Saqalli (2017) used the Century model to represent the soil dynamic and the plant growth. In addition, they use the automaton cellular to represent spatially the environment and the ABM to represent the crop production management by the farmers. The main question is how to integrate different types of models. For that, RECORD (Bergez et al. 2007, 2014) provides a framework for models integration for cropping system management. Crop2ML (Midingoyi et al. 2021) provides an open-source multi-language modelling framework for the exchange and reuse of crop model components. OpenMI (Gregersen et al. 2007; Harpham et al. 2019) provides interface for the integration of models from different origins.

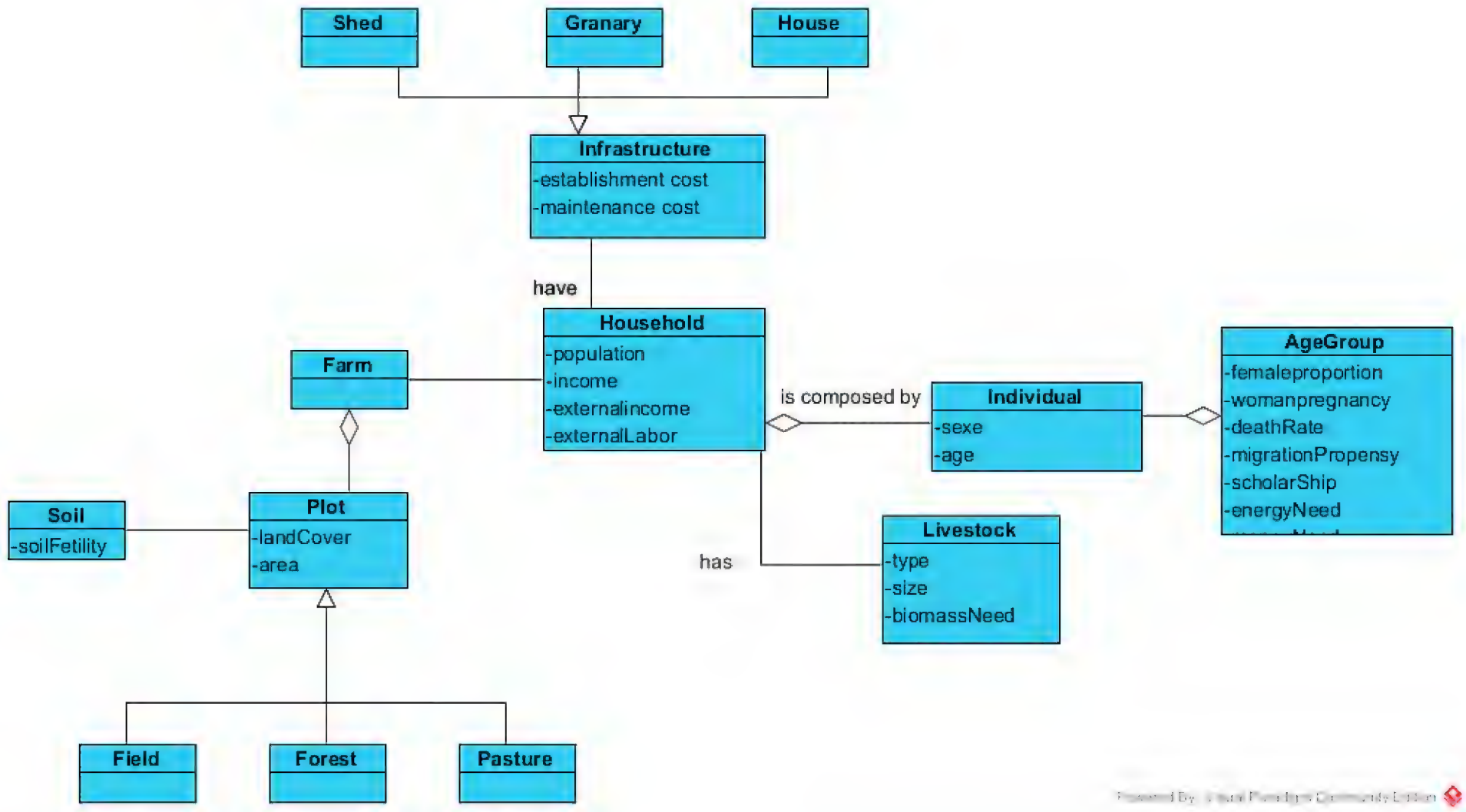

Figure 1. Meta-model for household structuration.

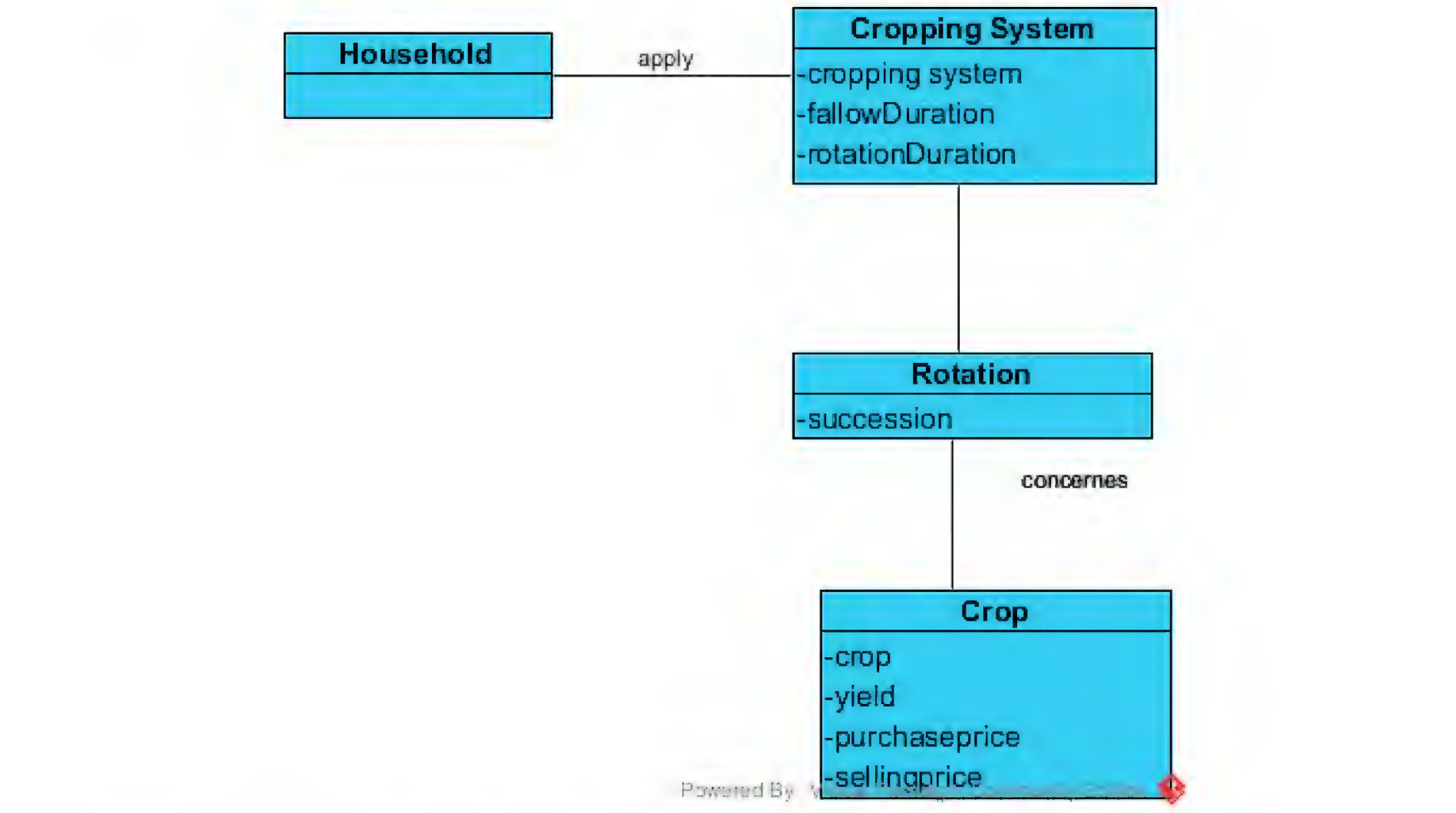

Figure 2. Meta-model for household cropping system strategies' definition

Unlike these previous platforms, Mimosa (Müller 2004) takes account the analysis, the design, implementation and simulation phases and it is not specific to a formalism. It provides framework to specify tools allowing a modeller to describe his model in his appropriate formalism as well as the simulation of these models (Müller 2004). Based on that, Mimosa can be considered as the most relevant framework for MAASSD application.

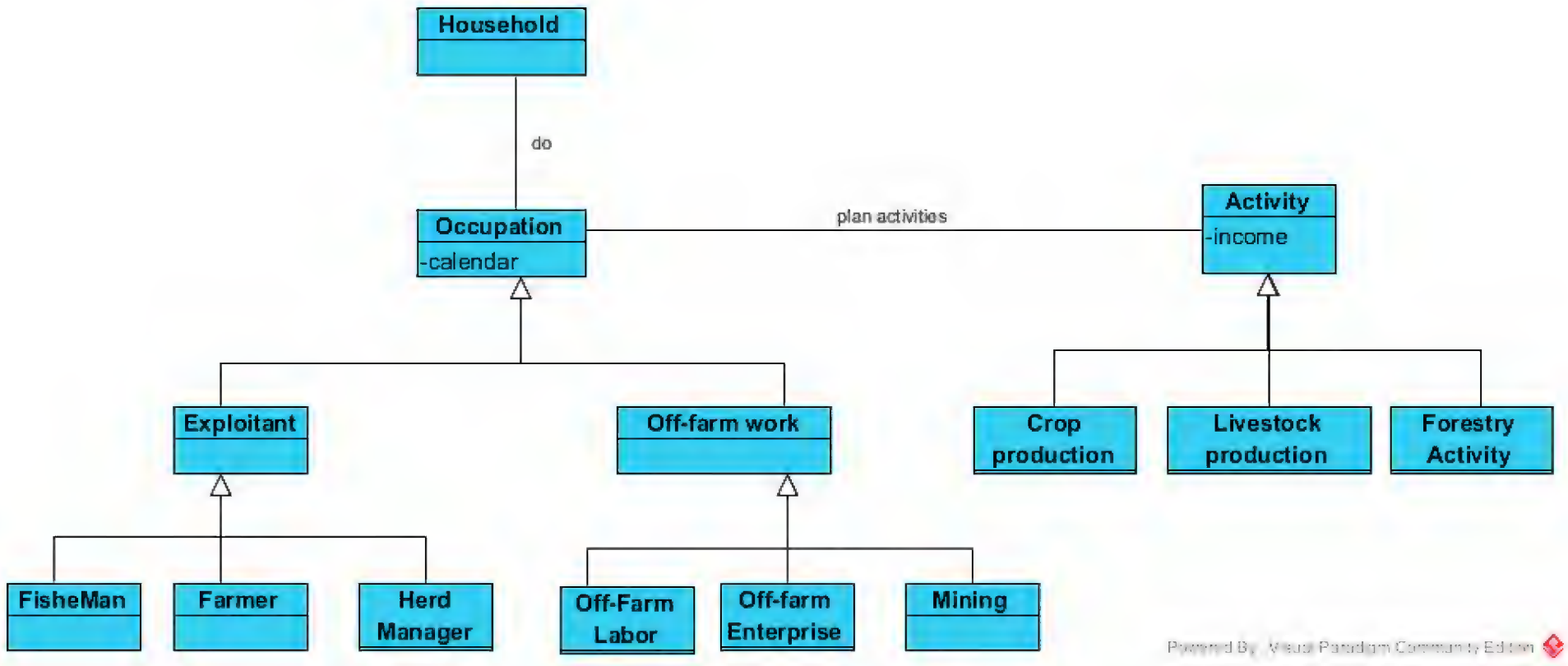

Figure 3. Meta-model for household occupations' definition.

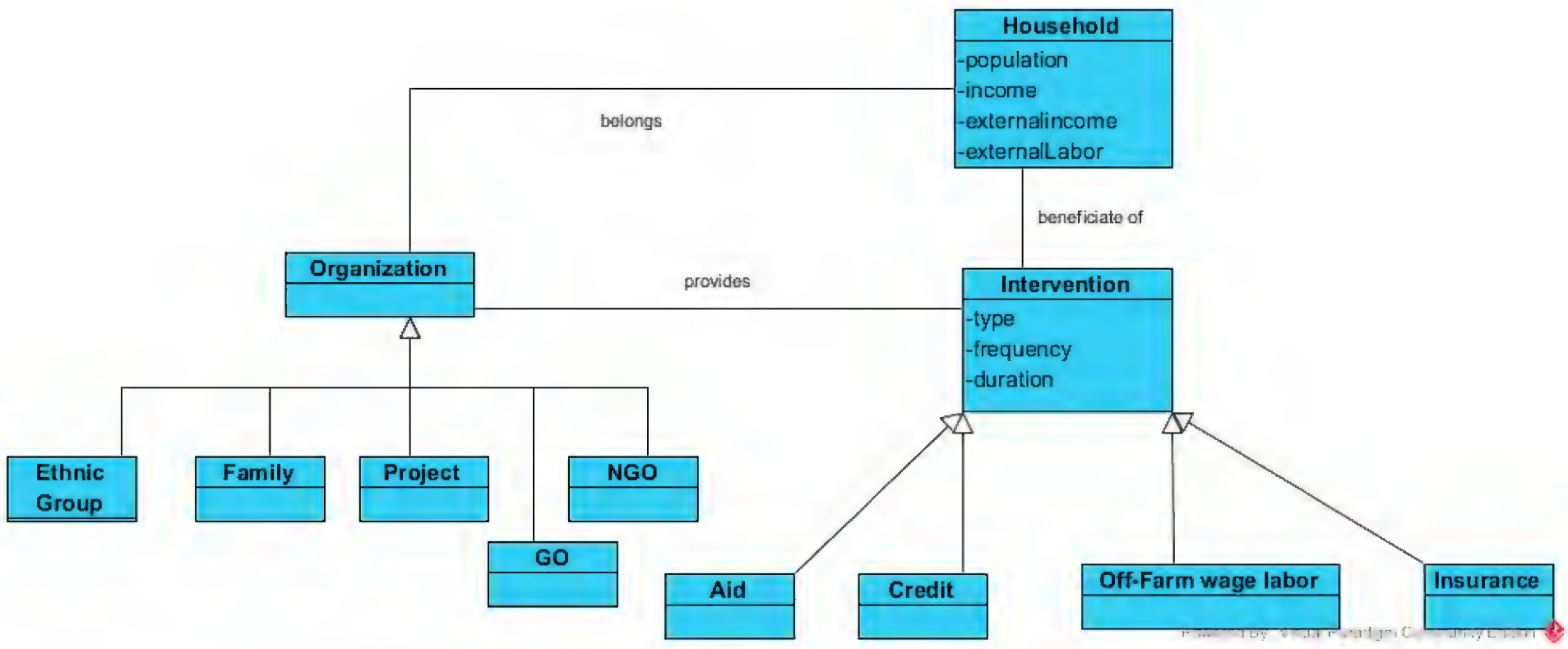

Figure 4. Meta-model for policies' definition.

Step 4: Model design

The objective of this step is to propose a modelling framework for designing the model. This framework comprises a meta-model (Fig. 5) and a simulation framework (Fig. 6). We recommend using the ODD protocol for the design process.

According to the meta-model, a model is based on interacting households. Each household comprises a set of individuals characterised by their sex and age. Each household belongs to an organisation that provides support through various interventions. Households apply a range of cropping systems that define their cropping management strategies. These strategies are applied at the farm level, which is composed of a set of plots.

The simulation framework defines the dynamics of the model. It comprises a set of possible parameters and three phases: initialisation, simulation and output generation.

Model parameters

The analysis of some dynamic models shows the importance of parameters. For example, ALMASS (Topping et al. 2003) integrates an important number of parameters to specify all types of animal. AnimSim (Parrott and Kok 2002) is a generic model for the representation of organisms of different types of species via the specification of appropriate sets of parameter values. In dynamic models, parameters take different forms. The first form concerns the simple parameters used to describe the evolution like, for example, the population growth rate etc. The second forms of parameters concern complex parameters used to initialise models structure and dynamical behaviour. They concern Geographical Information System (GIS) data used to initialise environment configuration, equations and models to simulate some processes depending on the contexts of application and parameters specifying the model structure and behaviour. For example, in Mirana (Aubert et al. 2010), different parameters types are used to initialise model structure and initial state, environment configuration, agent's behaviour through the definition of their needs (food, money etc.), objectives (production, conservation etc.), planning mechanism, norms and interactions. The use of various parameters types in Mirana provides a high flexibility to simulate a range of systems and scenarios. In this section, we propose a set possible parameters that one can use. These parameters concern the crop and cropping system description, the socio-economic data and finally the biophysical data (Table 5).

Model initialisation

The model initialisation comprises the environment configuration and the population generation.

Table 5. Possible parameters in agricultural model.

Crop and cropping systems parameters	
Types	Description
Crop	Identification and characterisation of major cultivated crops
Cropping system	Identification and description of the major cropping system
Crop rotation	For each cropping system, defines the related crop rotation and fallow management
Socio-economic parameters	
Input	Description
Household	Describes the household typology in the farming system (farmer type, family size, farm size, number of external workers, off-farm income, in-farm income, livestock size, family budget, number of granary, number of granary, shed and houses, equipment used for the production, cropping system, ethnic group and participation to different organisations)
Household structure	For each household type, describes the structure of household population (by age group, sex repartition, labour provided, money need, off-farm income)
Food sharing	Define the use of different crops in the feeding and selling (% of each crop in feeding and in selling)
Herd	Describes the type and number of animals (beef, sheep and goat) for each household type
Supports	Describes the different kind of support that each household type beneficiate (aid for cash, aid for food, crop insurance, seed provision etc.)
Crop prices	The crop prices in the different periods
Biophysical data	
Input	Description
Climate data	

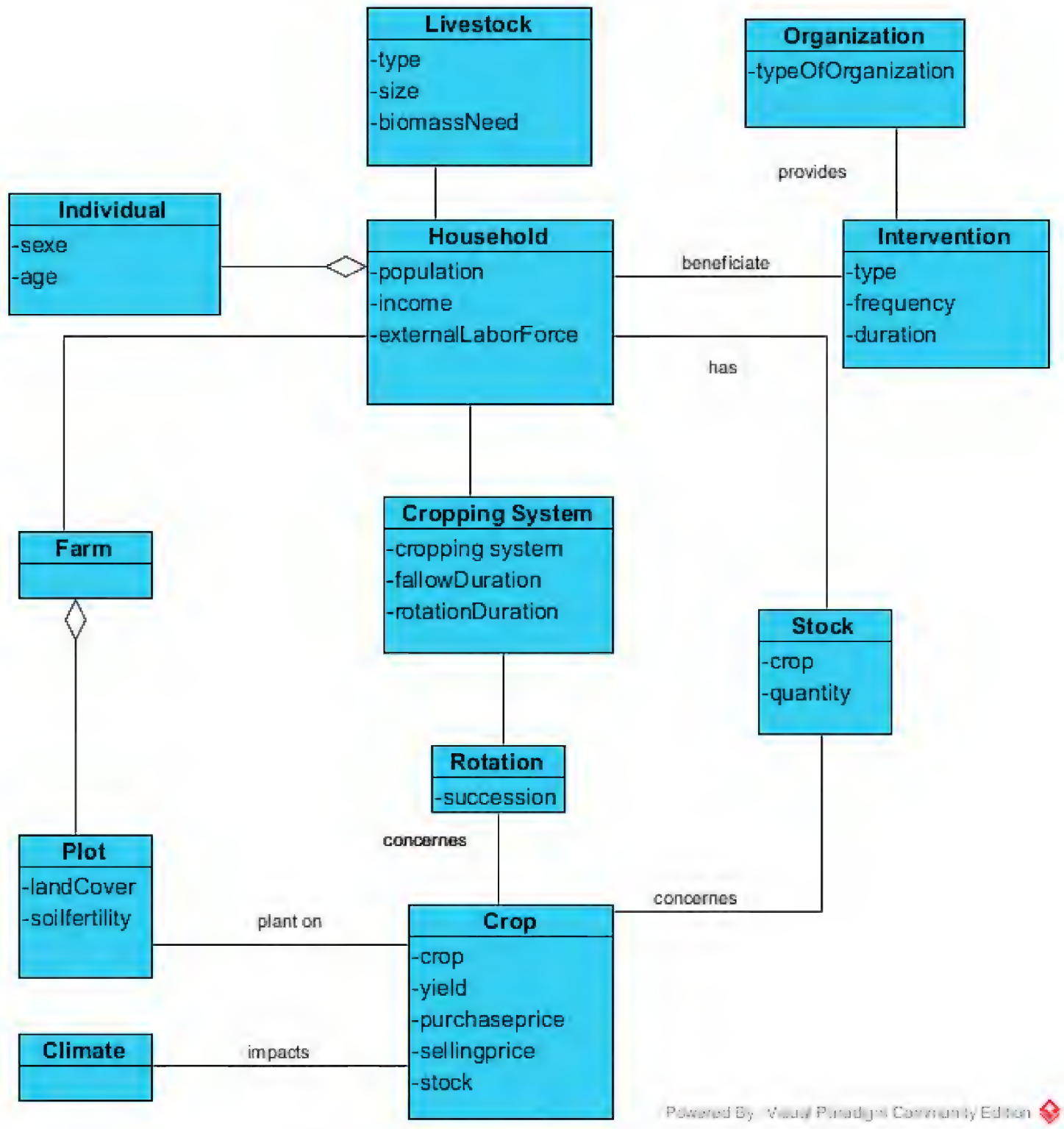

Figure 5. Meta-model of ABM for agricultural system simulation.

Environment configuration

The objective is to create a simulation environment. This environment represents the biophysical condition of the agent, specifically its spatial configuration. Spatially, the environment is represented as a set of plots. Each plot is characterised by a soil type, which defines its properties and a land-use and land-cover type. After defining the spatial configuration, the climate conditions are defined spatially.

This phase uses land-cover data, climate data and soil data as input. These data can be collected from the site under study or from public sources.

Population generation

The objective is to generate households and individuals for simulation. The synthetic population can then be used to generate the population. Individuals are assigned to households according to their type. Crop and animal production systems are then assigned to households according to their initial description. Finally, a farm is assigned to each household.

This step is based on household data, crop management data, animal management data and population scenario data. These data can be extracted from surveys conducted at the study site or from public data sources.

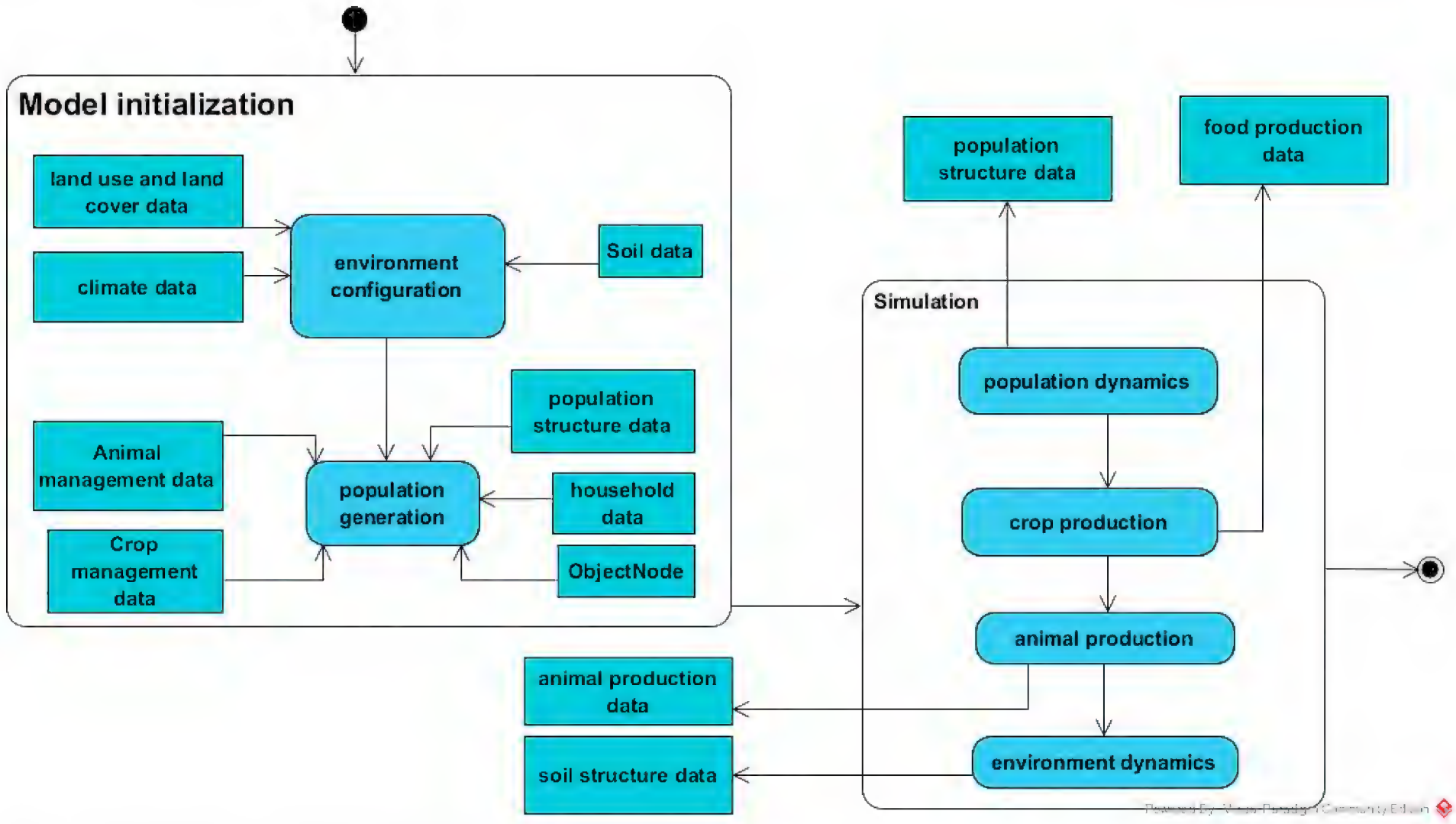

Figure 6. Simulation framework of the agricultural system.

Phase 2: Simulation

The model dynamics comprise the population simulation, the livestock production, the crop production and environment dynamics.

Population simulations

The dynamic of demography is characterised by the natality, ageing and mortality of the individual. The natality depends on the population growth rate and it is defined scholastically. An individual can give birth randomly according to the birth rate. The individual age is incremented yearly. According to the change in people's age, individual changes age group that determines the probability of mortality. The individual death is determined scholastically. A probabilistic function determines the death of an individual depending on the mortality death rate on the individual age group.

Crop production

Household produces crop according on the food and money need, the available land, the labour force and the need in inputs. Then, household defines the food needs and money according to the household size as follows. Based on the money, the food need and labour force, household determines the area to be cultivated for each crop.

The plots are cultivated according to the crop sequence used by the household. At the end of the cropping season, household harvests crop and stores the crop production. Crop production depends on the crop yield and the cultivated area. Finally, a part of the crop production is used as food and the remainder is sold for income generation.

Environment dynamics

The environment dynamics concern the interactions between soil-plant-atmosphere depending on the objective of the study. These dynamics simulate the impacts of human activities on environment and vice-versa. These dynamics can be represented basically or using external model such as STICS (Beaudoin et al. 2023),Century (Parton 1996) etc.

Phase 3: output generation

A range of data can be generated from the simulation. This output data exist at individual level, household level, climate and the population. (Table 6).

Table 6. Output data.

Individual_output	Id, age, sex, migration experience,	Provides the output data on each individual simulated in the model.
household_output	Id, type, crop production, income, family size, cultivate d area, Number of migrants by household	Provides the output data on each household simulated in the model.
Climate	Minimal and maximal temperatures, rainfall	Provides the climate data of the simulated year.

Step 5: Model implementation

We propose the use of rapid prototyping to implement the model. Rapid prototyping is the quick development of a prototype model. A prototype model is a simplified version of the final model. It enables the expected behaviour of the model to be defined and discussed. Prototyping reduces development costs and facilitates discussion between users and developers. In addition, it facilitates the verification of specifications (Hilaire et al. 2000). In simulation, prototyping can be used to communicate which actors (modellers, scientists and stakeholders) are involved in model development and to analyse how different scenarios can be taken into account. To achieve this, the modeller can build a prototype for each scenario to identify the relevant variables, before finally building the final model.

Experimentation

Study sites

Our study covers the country of Burkina Faso. Burkina Faso is a country of migration. The migration in Burkina Faso is international and internal. In this study, we are concerned by the inter-provincial migration. The administrative division of Burkina Faso is composed of 45 provinces shared amongst 13 regions.

From climatic point of view, Burkina Faso is characterised by three climatic-zones (Fig. 7): Sahelian, Sudano-Sahelian and Sudanian zones:

- The Sahelian zone in the north with an average annual rainfall lower than 600 mm, a high rate of evapotranspiration as well as high temperatures and a short rainy season (2 to 3 months). It is the zone with the lowest rainfall in the country;

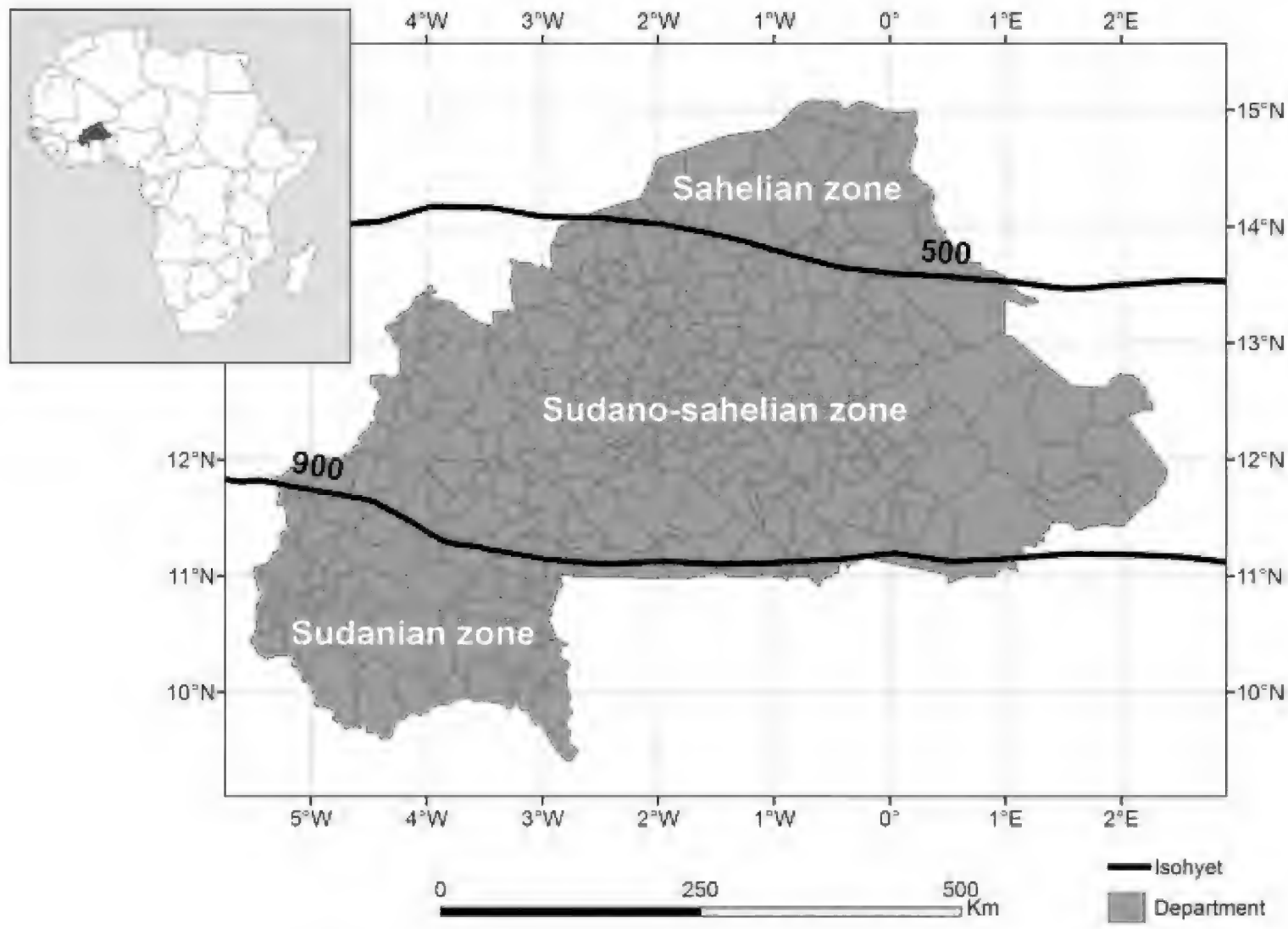

Figure 7. Climatic zones of Burkina Faso.

- The Sudano-Sahelian zone in which the rainfall varies between 600 and 900 mm over 4 to 5 months. It comprises the most extensive climatic zone as it extends over all of the central part of the country. The temperatures recorded are generally mid-range (between 20 and 30 °C).
- The Sudanese zone occupies the southern part of the country, where the rainy season lasts from 5 to 6 months with the level of rainfall attaining or even exceeding 1100 mm annually. This area is marked by low temperature ranges (20–25 °C).

Model design

Our modelling approach aims to represent the feedback loop between agricultural dynamics and migration. In this research, we adopted an agent-based modelling approach to represent household migration decision-making in the context of climate change, land management and crop production decision-making and the impact of these factors on migration decisions, as well as the impact of social networks on individuals' propensity to migrate. The model's architecture integrates a climate module, a crop production module, a biophysical model and a data management module.

To provide an explicit representation of the social network, we use the Small-World approach to depict the relationships between agents in the model (Fig. 8).

The model is multi-scale as it takes into account articulations between farm, household, individual and local levels (Fig. 8). The individual's decision to migrate depends on the household's capacity to satisfy its needs. An individual will migrate if their household cannot satisfy their needs (for food and money) due to the climate of the locality (Fig. 9). In return, the individual contributes to household income and the workforce.

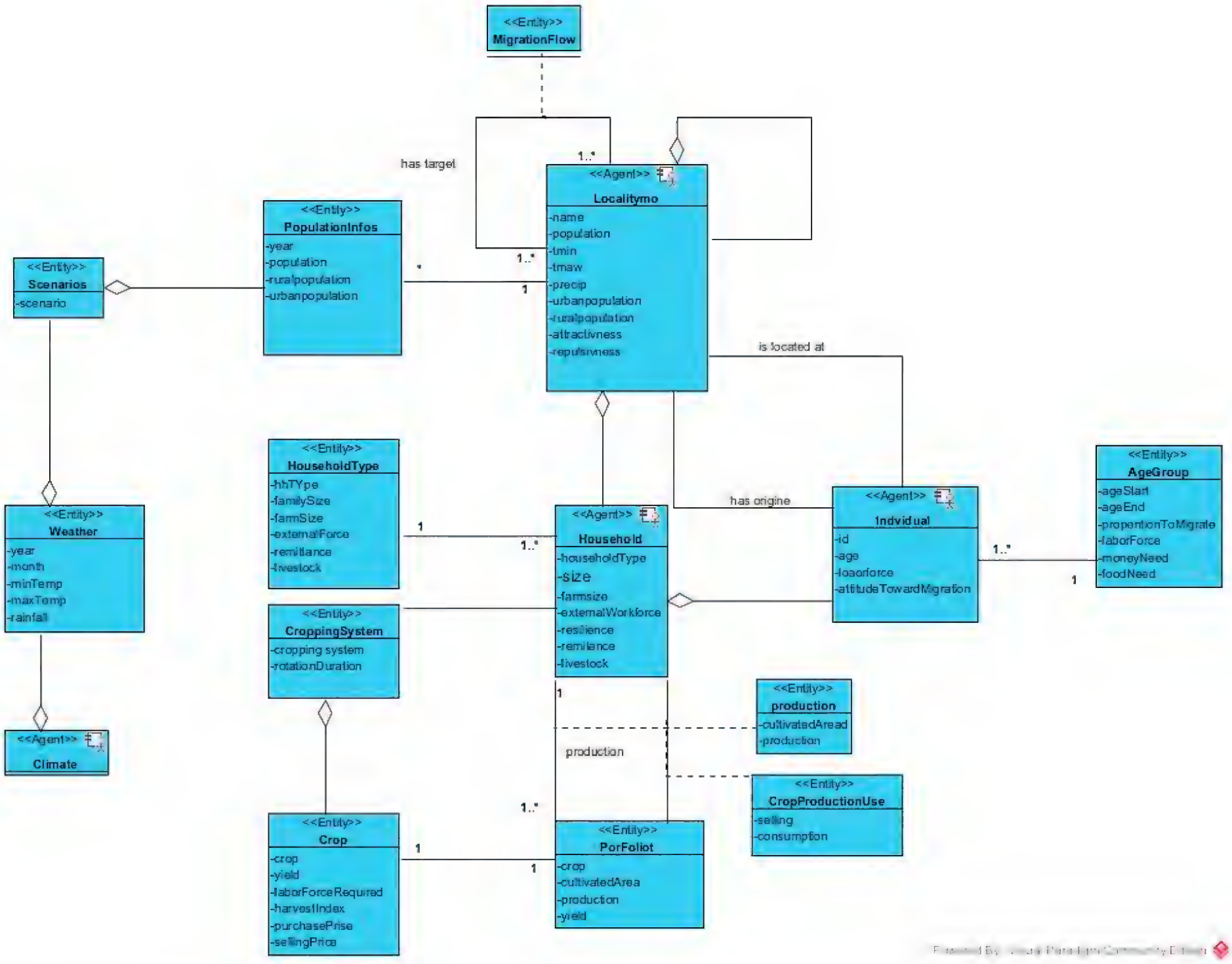

Figure 8. Conceptual model.

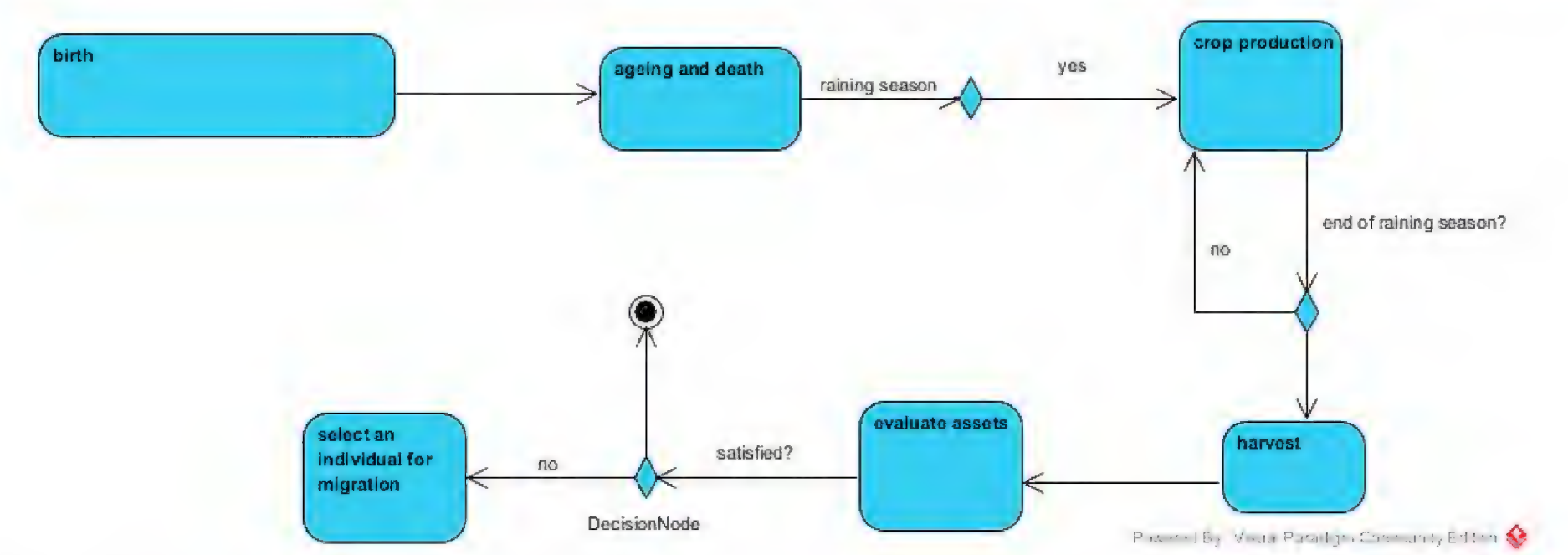

Figure 9. Household and individual dynamics.

Implementation

The model implementation is based on the GAMA platform (Grignard et al. 2013). GAMA is an open-source modelling and simulation environment for creating spatially explicit agent-based simulations. It is widely used in several domains, including urban mobility, climate change adaptation and epidemiology. GAMA is based on GAML, a language specifically designed for modelling and

simulation. It enables users to build integrated models incorporating different modelling paradigms, explore and calibrate their parameter space and run virtual experiments with powerful visualisation capabilities. GAMA also integrates functionalities that facilitate the creation of social networks, the import of GIS data and the multi-scale representation of systems.

Simulations Configuration

All the simulations have focused on the Province of Boulkiemdé. It lies between 12°14'59"N, 2°22'03"W. Located in the central part of Burkina Faso, it is bordered by the Provinces of Passoré to the north, Kourwéogo to the north-east, Kadiogo to the east, Bazèga to the south-east, Ziro and Sissili to the south and Sanguié to the west. It covers an area of 4,269 km². The provincial capital, Koudougou, is 100 km from Ouagadougou, the capital of Burkina Faso. Finally, the Province of Boulkiemdé is situated in the Soudano-Sahelian climatic zone.

The simulations involved a population of 400 individuals, shared amongst 40 households. These households are divided into four categories (Table 7): small farmers with lower potential (type 1), small farmers with higher potential (type 2), large farmers with low potential (type 3) and large farmers with higher potential (type 4). The objective of the simulations was to assess the impact of climate shocks on migration and the resilience of different household groups under different climate scenarios. Household data were extracted from the Agriculture Ministry Database. These data concern household type, number, size, cultivated area, most important crops, income and livestock size.

Table 7. Description of simulated households.

Description	Household type	Household size	Farm size	TLU	Crop rotation
small farmers with lower potential	type1	8	4	6.8	Maize. Milet. Sorghum. Sorghum
small farmers with higher potential	type2	8	4	4.5	Maize. Milet. Sorghum. Sorghum
large farmers with low potential	type3	15	6	4.9	Maize. Sorghum. Sorghum. Sorghum
large farmers with higher potential	type4	16	10	6.2	Maize. Sorghum. Sorghum. Sorghum

We have identified three climate scenarios, which are based on the likelihood of a climate shock occurring. The first is the wet scenario. We assume that there is a 30% probability of a drought season occurring. The second scenario is moderate, with a 50% probability of a drought season. The third scenario is a drought scenario, with a 70% probability of a drought.

In the model, crop yield depends on season quality, which influences assets and migration decisions.

Each scenario was simulated for 45 years and the results were compared.

Results of the simulations

Climate shocks and migration

The results showed that climate seriously impacts migration decisions. The most significant migration trends were observed in Scenario 3, where drought was a key factor (Fig. 10). The population is therefore likely to mi-

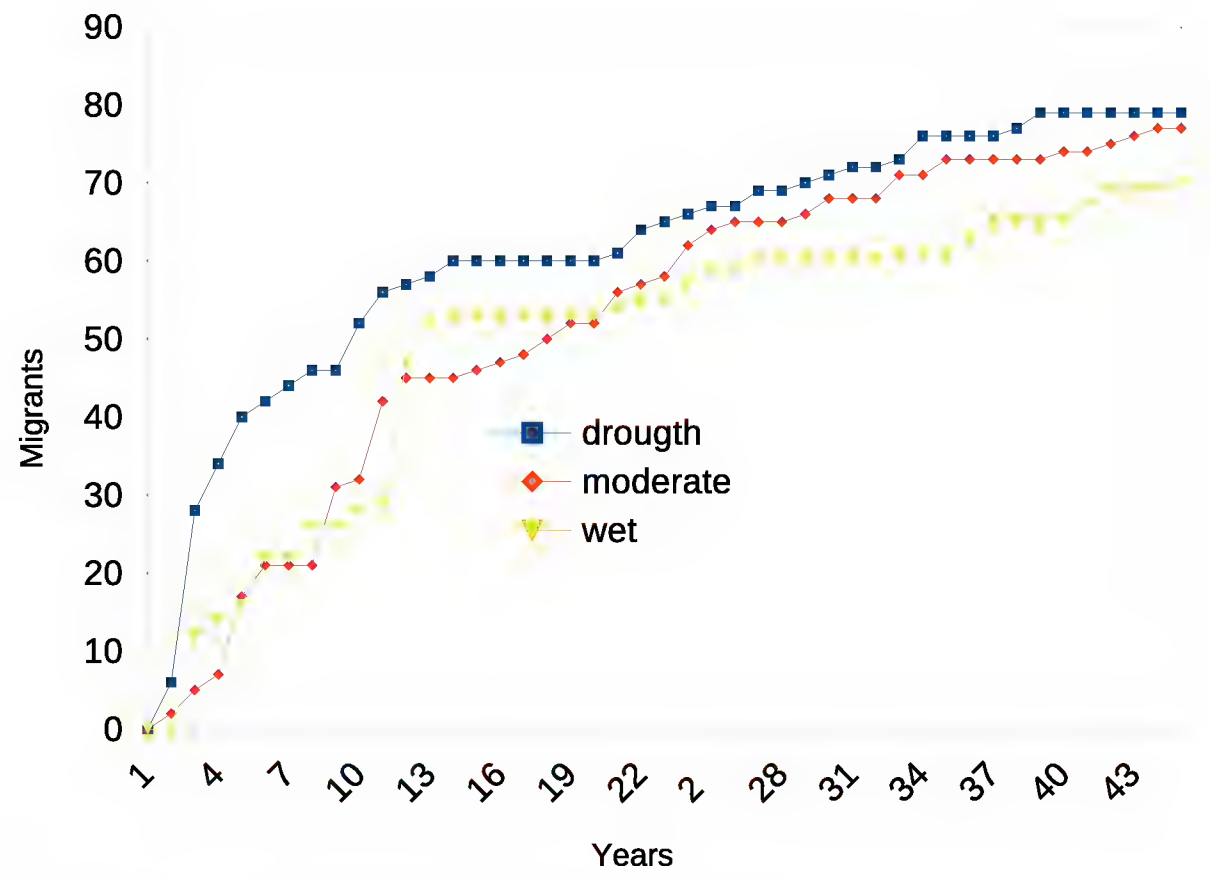

Figure 10. Migration trends in different climate scenarios.

grate when climate conditions are unfavourable. In Scenario 3, the probability of a drought is highest. Under these conditions, households cannot meet their food and income needs and consequently use migration as an adaptation strategy.

Migration as strategy of adaptation

To assess the strategies of different groups of households under different climate scenarios, we compared the number of migrants from each household type. The results showed that, in all scenarios, types 3 and 4 have the highest number of migrants (see Figs 11, 12), while type 1 had the lowest. The simulations showed that types 3 and 4 were the most vulnerable to climate shock and were most likely to migrate. Additionally, the results showed that type 2 households are the most resilient to climate shock.

Discussion

This study aimed to propose a methodology for designing and implementing agent-based modelling (ABM) for simulating agricultural systems in developing countries. The methodology addresses both the conceptual and the simulation model development. The methodology proposed in this study is generic and takes into account knowledge integration and sharing, multi-scale representation of the agricultural system and the heterogeneity of human behaviour."A methodology is a collection of methods covering and connecting different stages in a process. The purpose of a methodology is to prescribe a coherent approach to solving a problem within a software process by selecting and relating a number of methods in advance" (Ghezzi et al. 1991). Our methodology is based on MAS, ODD, ARDI and Bommel methodologies to create a unique approach. However, our methodology differs from these existing methodologies in that it concerns the agricultural system.

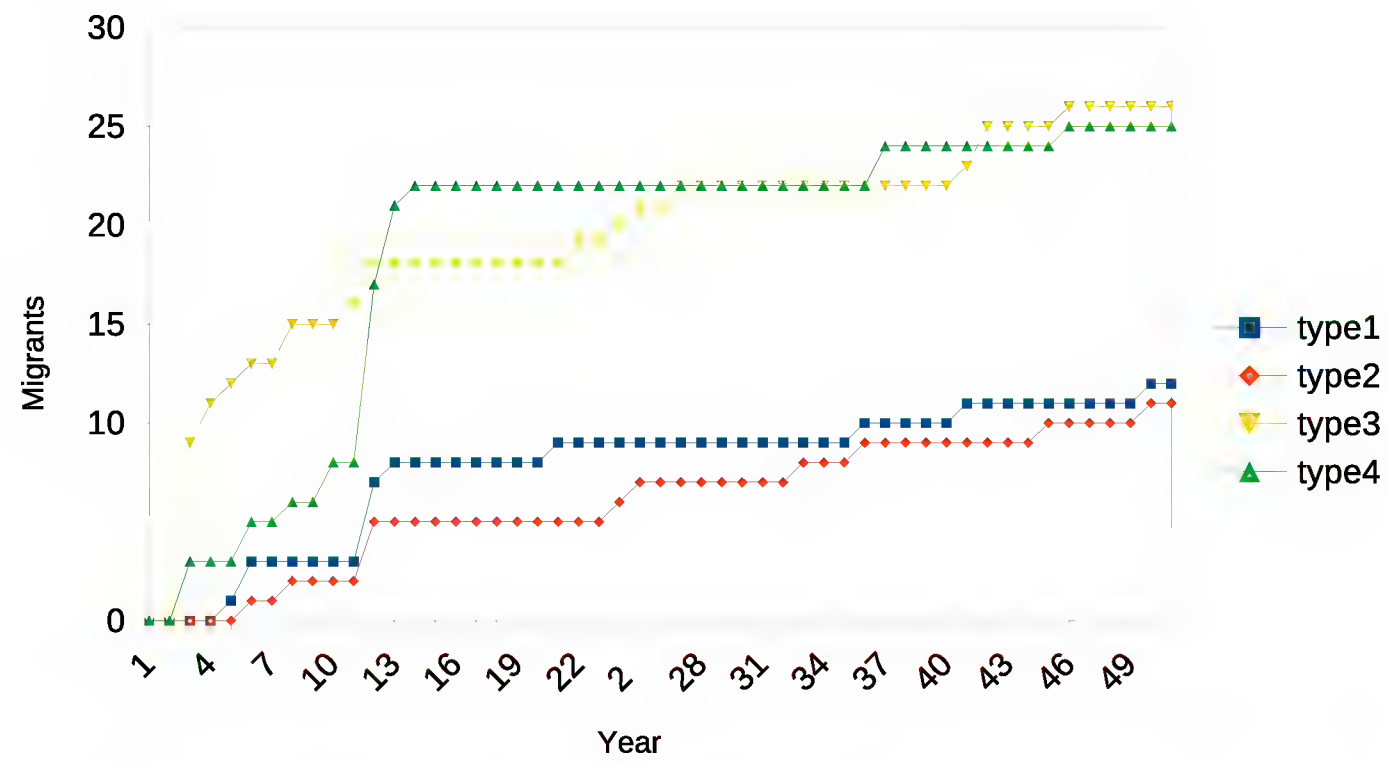

Figure 11. Impacts of climate scenario 1 on migration of different categories of households.

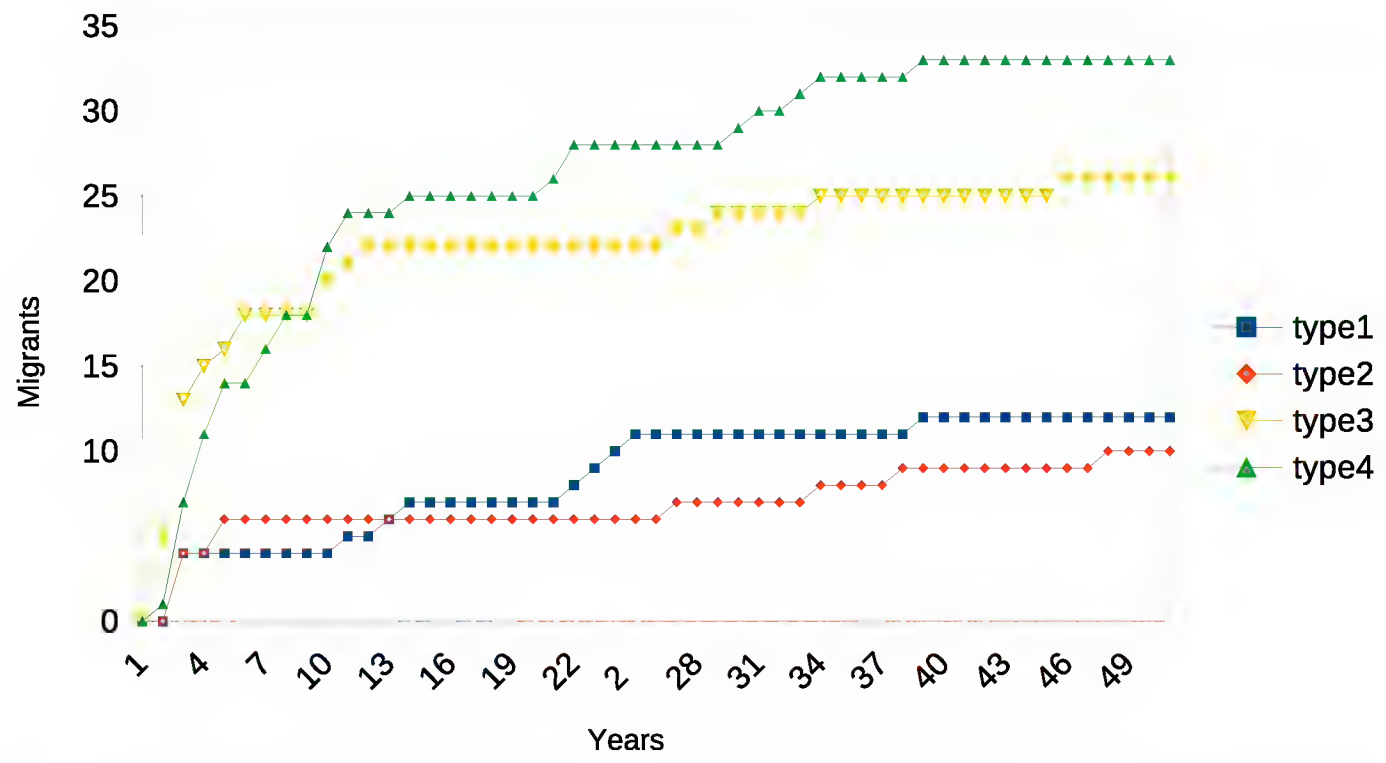

Figure 12. Impacts of climate scenario 3 on migration of different categories of households.

Methodology typically starts from a meta-model identifying the basic abstraction to be exploited in development (Cernuzzi et al. 2005). A meta-model can be viewed as a model which provides a particular representation of a system and can be used to define specific models. In others words, a meta-model is a model of a model with a high level of abstraction. In this study, we proposed not only a methodology, but also two meta-models. The first one can be extended to propose a domain model. The objective is to identify the main information manipulated in the target system. The domain model allows knowledge integration between various stakeholders to provide a common understanding of the target system. As to the second one, it can be extended to propose a conceptual model for ABM simulation. The meta-models proposed in this study are closed to agricultural system and easier to be understood by the designers. All of that is associated with a simulation framework providing the basis for model design, development and simulations. Additionally, the use of a meta-model makes it easier to model by extending the MAASSD meta-model.

Stakeholders Engagement

MAASSD methodology pays a particular attention to the stakeholders' engagement as the stakeholders are engaged in all stages of the methodology. That ensures a smooth model development process: "while the participants may determine the questions that the model should answer and may supply key model parameters and processes, the structure of the model must be scientifically sound and defensible" (Voinov et al. 2016).

Study limitations

Although we propose a methodology for ABM for agricultural system simulation, this study does not take account the scenarios development, simulation and validation phases. In addition, this study did not implement a tool for model development and simulation.

Conclusions

This study enabled the development of the first methodology for simulating agricultural systems in developing countries. The main objective was to avoid duplication of modelling efforts in this field using agent-based modelling (ABM) and to propose a unique framework.

Two literature reviews were conducted. The first assessed existing MAS and ABM methodologies. The second assessed the application of ABM to agricultural system simulation. While the existing MAS and ABM methodologies are not specifically designed to represent agricultural systems, they provide a basis for developing a new methodology for agricultural system simulation. The second review revealed the disparity in the application of ABM in agricultural system simulation and showed that they are not replicated in other contexts, highlighting the importance of our study.

Based on these observations, we have proposed the MAASSD methodology. This methodology is based on ABM to capture farmer heterogeneity and fully represent the interactions between human decision-making and environmental dynamics, as well as providing a multi-scale representation and integrating knowledge from stakeholders of different origins. Finally, the methodology was applied to simulate the impact of crop production on migration in the context of climate change in Burkina Faso. This experiment demonstrated the methodology's ability to model the agricultural system.

As a perspective, MAASSD methodology would be experimented in a large number of contexts to show its effectiveness to represent the agricultural system in developing countries.

Additional information

Conflict of interest

The author has declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

AI was used to correct the english.

Funding

No funding was reported.

Author contributions

The author solely contributed to this work.

Data availability

All of the data that support the findings of this study are available in the main text.

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